FORMATION OF IMPLANTED PIEZORESISTORS UNDER 100-NM THICK FOR NANOELECTROMECHANICAL SYSTEMS

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ABSTRACT

Piezoresistors with a thickness of 90 nm have been obtained by implanting boron fluorine into germanium-preamorphized silicon. Germanium implantation was carried out at a dose of 10^{15} cm^{-2} and an energy of 60 keV to form a 80-nm-thick preamorphized layer prior to BF_2 implantation at a dose of 5×10^{14} cm^{-2} and an energy of 15 keV. The experimental sensitivity is 80 % of the theoretical maximum. This shows that the germanium preamorphization step does not impact the sensitivity of the piezoresistors. Moreover, 1/f noise characteristics have been improved compared to those obtained in a previous workwithout using a preamorphizing implant.

INTRODUCTION

NEMS (NanoElectroMechanical Systems) exhibit highly promising features. They allow very high resonant frequencies to be obtained with very high force sensitivities. As mass sensors, they offer unprecedented sensitivities with a mass resolution of a few hundred Daltons. It even seems possible to reach a mass resolution as low as 1D in the near future [1].

Another important feature is that NEMS are made of silicon. Hence they allow actuating and sensing functions to be integrated. This leads to a more compact system supporting parallel operations provided dedicated multiplexed signal processing is used.

It seems also advantageous to scale MEMS to submicron dimensions especially when dealing with piezoresistive properties : Recently, Toriyama et al. [2] have demonstrated that the longitudinal piezoresistive coefficient of nano wire piezoresistors could be increased up to 50 % compared to the classical value.

Piezoresistive cantilevers are now intensively used for atomic force microscopy [3]. They also constitute a promising approach as sensors for detecting chemical and biological interactions [4].

The most challenging issues lie in that the surface-to-volume ratio increases when the NEMS dimensions decrease. This may be problematic especially for high mechanical quality factors. Moreover, as the dimensions of NEMS decrease, integrating the actuating or sensing functions within the device becomes more difficult. Therefore, dedicated fabrication techniques at the nanometer scale are needed.

For example, as pointed out by Harley et al. [5-6], for a piezoresistive cantilever, an increase of the sensitivity can be achieved through a reduction of the cantilever mass without impacting the bandwidth of the system. This implies to reduce the thickness of the cantilever but it becomes more and more problematic to reduce in the same proportion the thickness of the piezoresistive layer. New ways for fabricating ultra-shallow piezoresistive layers are therefore needed. Harley et al. have demonstrated that highly sensitive piezoresistive cantilevers can be obtained using vapor-phase epitaxy [5]. One drawback of this technique is that the quality of the interface between the epitaxial layer and the substrate is critical since it impacts the device performance especially the noise characteristics.

As complementary metal-oxide-semiconductor (CMOS) technology progresses rapidly towards the sub-100 nm device dimensions, ion implantation continues to be the technology of choice for obtaining ultra-shallow p^+/n junctions.

Studies based on recent developments of the CMOS technology have shown that using BF_2 implantation instead of boron implantation leads to the formation of thin p^+ layers (<180 nm) well suited for fabricating ultra-sensitive piezoresistive cantilevers [7]. In this paper, we demonstrate that piezoresistors with a thickness of 90 nm can be obtained by implanting BF_2 into germanium-preamorphized silicon. The conventional purpose of preamorphization is to minimize the channeling effect of boron. Moreover, it serves as a barrier to the back-flow of free interstitials to reduce boron transient enhanced diffusion (TED) [8]. It also favors the electrical activation of implanted boron atoms.

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FABRICATION

The fabrication process is similar to the one reported in [7] except that a preamorphization step is included in the process before implanting the boron fluorine. The preamorphization step consists in implanting germanium ions in the substrate at an energy and a dose that are carefully chosen so as to permit that the implanted boron profile is well confined within the preamorphized layer.

The implantation and annealing conditions are critical and must be chosen judiciously since they also impact the electrical properties of the device. In our case, germanium was implanted at an energy of 60 keV and a dose of 1 x 10^{15} cm^{-2} to form a 80-nm-thick preamorphized layer prior to the boron fluorine implantation at an energy of 15 keV and a dose of 5 x 10^{14} cm^{-2}.

After a rapid thermal anneal (950°C for 15 s) and a conventional one (850°C for 20 min), a 90-nm-thick piezoresistive layer is obtained at a background concentration of 1 x 10^{18} cm^{-3}. This is 40% thinner than the one obtained without preamorphization. This effect is clearly visible when comparing the boron profiles with or without the preamorphizing implant (see Fig. 1 and Fig. 2).

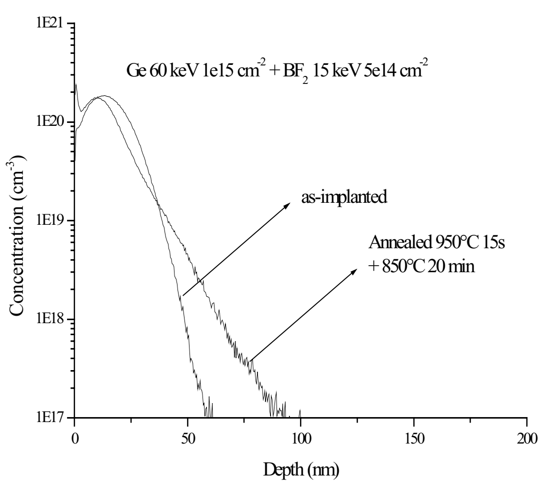

Fig.1 *: SIMS profiles of boron implanted in a germanium-preamorphized substrate before and after annealing.*

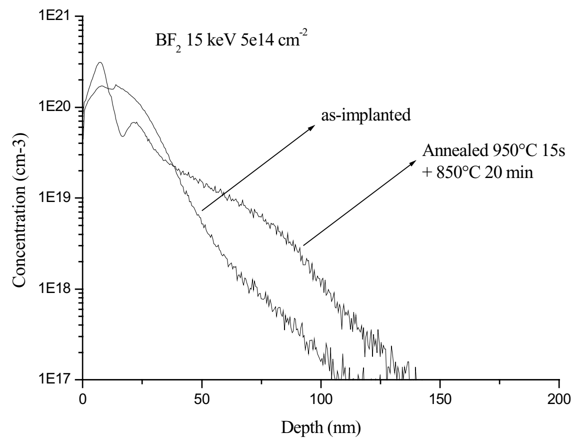

Fig.2 *: SIMS profiles of boron implanted in a non preamorphized substrate (crystalline substrate) before and after annealing. Note that except the preamorphization step, the implantation and annealing conditions are the same as those used in Fig. 1.*

Moreover, for a given thermal budget, the electrical activation of boron is also improved for a pre-amorphized sample compared to a non pre-amorphized one. This can be explained by the fact that a preamorphization step leads to the formation of an almost perfect crystalline layer after the solid phase epitaxy (SPE) that occurs during annealing : the clustering effect of boron no longer appears on the SIMS profile after annealing for the preamorphized sample and the migration of boron atoms to the substitutional sites during SPE improves electrical activation. The boron clustering no longer appears with the preamorphized sample. This effect can be clearly seen when comparing Fig.1and Fig.2.

CHARACTERISTICS

The performances of 10-µm-thick, U-shaped piezoresistive cantilevers were studied to evaluate the impact of the preamorphization step on the electrical properties. A scanning electron microscope (SEM) image of a typical U-shape piezoresistive cantilever is shown in Fig. 3.

An experimental setup developed for the electrical characterization of nanostructures has been used to determine the sensitivity of the cantilevers [9]. It includes a multiprobe microcontactor made of an array of metallic cantilevers inserted in an atomic force microscope (AFM) with a low noise nanopositionning stage.

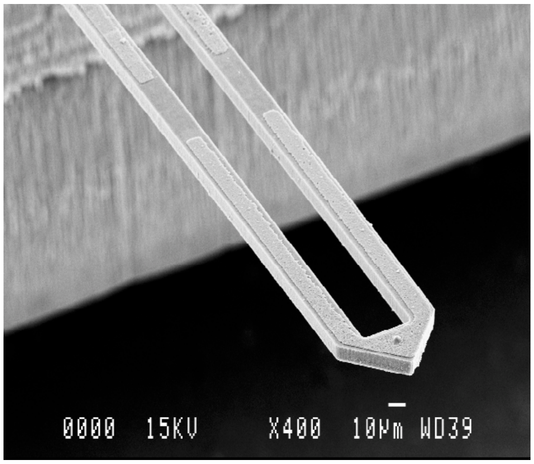

Fig.3 *: SEM image of a 8-µm-thick, 370-µm-long germanium-preamorphized piezoresistive cantilever.*

As shown in Table I, it appears that, as in the case of BF_2 implanted piezoresistors [7], the sensitivity is excellent and about 80% of the theoretical maximum.
This demonstrates that provided the piezoresistor is well confined at the surface of the cantilever, the germanium preamorphization step does not impact the sensitivity if the implantation and annealing conditions have been judiciously chosen. In actual fact, this step is critical since the depth of the preamorphized layer obtained by implanting germanium should be thick enough to suppress the boron channeling. On the other hand, it is well known that increasing the energy of germanium implantation to obtain a thicker amorphized layer will lead to a higher density of extended defects that will impact the electrical properties of the piezoresistors. A compromise must be therefore obtained to reduce both the channeling effect and the density of extended defects.

In our case, the germanium implanted at an energy of 60 keV and a dose of 1×10^{15} cm^{-2} permits to obtain a 80-nm-thick preamorphized layer. It leads to a steeper boron profile compared to the one obtained without a preamorphization step by suppressing the well-known channeling effect of boron.

Table I *: Electrical properties of germanium-preamorphized piezoresistive cantilevers.*

Length (µm)	320	370	420	470
Calculated sensitivity ($\Delta R/R$) $Å^{-1}$	6.67e-7	4.89e-7	3.76e-7	2.95e-7
Measured sensitivity ($\Delta R/R$)/ $Å^{-1}$	5.04e-7	3.89e-7	3.07e-7	2.29e-7
$\beta= [(\Delta R/R)_{meas}/(\Delta R/R)_{cal}]$	**0.76**	**0.80**	**0.82**	**0.78**

An another important point was to study the influence of the preamorphization step on the noise characteristics. Noise measurements were performed with a DC bias system using batteries in order to minimize the spurious signals coming from the electrical network, a probe station, a low noise transimpedance amplifier and a Fast Fourier Transform analyser.

Fig. 4 shows a typical noise spectrum obtained with a 370-µm long germanium-preamorphized BF_2 implanted piezoresistive cantilever. The 1/f noise characteristics are improved by an order of magnitude compared to those obtained for the same conditions of implantation and annealing with piezoresistors without preamorphization as shown in Fig.5. As already mentioned, the recrystallization of the preamorphized layer during the Solid Phase Epitaxy leads to the formation of an almost perfect crystalline layer. Nonetheless, the 60-keV germanium implanted preamorphized layer annealed by RTA at 950°C during 15 s does not permit to recover the crystal lattice since beneath the former amorphous/crystalline interface EOR defects are formed. Reducing the energy of the amorphizing implantation down to 30 keV could be a solution since this will lead to the formation of a lower density of extended defects with a amorphized layer thick enough to minimize the boron channeling effect. Therefore, 1/f noise characteristics could be further improved. It should be also pointing out that the amorphizing energy can be reduced when reducing the implantation energy of boron. For example, a preamorphization energy of 5 keV is high enough to suppress the channeling effect when implanting boron fluorine at 1 keV and will avoid the formation of extended defects.

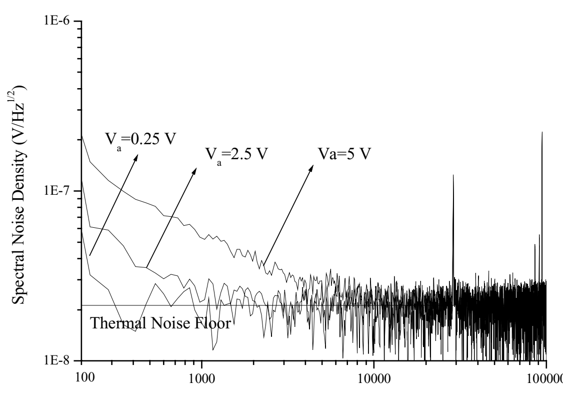

Fig.4 *: Spectrum noise density at various applied voltages for a 370-µm-long germanium-preamorphized BF_2 implanted piezoresistive cantilever.*

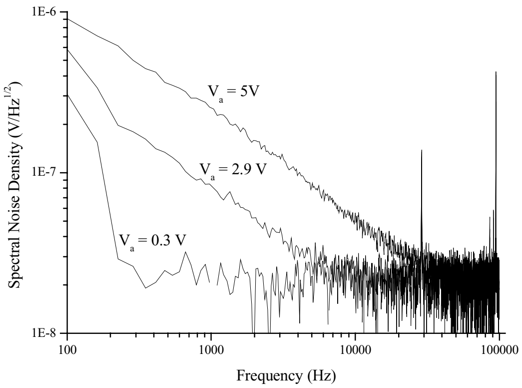

Fig.5 *: Spectrum noise density at various applied voltages for a 370-µm-long non preamorphized BF_2 implanted piezoresistive cantilever.*

CONCLUSION

In conclusion, we have shown that ultra-shallow and very sensitive piezoresistors can be fabricated by implanting BF_2 into germanium preamorphized silicon. The measured sensitivity is almost 80% of the theoretical maximum. Moreover, by reducing the germanium implantation energy (under 5 keV) as well as the BF_2 implantation energy (under 1 keV), the thickness of the piezoresistors could be further reduced down to 30 nm or less.

Novel annealing techniques such as spike rapid thermal annealing or laser annealing for reducing the thermal budget of the subsequent anneals could be also used to decrease the thickness of the piezoresistive layer [10-11].

Combining these techniques will open new ways for the fabrication of smaller and more sensitive piezoresistors well suited for Nano-Electro-Mechanical Systems.

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REFERENCES

[1] M.L. Roukes, "Nanoelectromechanical Systems", *Transducers'01/Eurosensors XV*, Munich, June 10-14th, 2001, pp. 658-661.

[2] T. Toriyama, Y. Tanimoto and S. Sugiyama, "Single crystalline nano wire piezoresistors for mechanical sensors", *Transducers'01/Eurosensors XV*, Munich, June 10-14th, 2001, pp. 1002-1005.

[3] M. Tortonese, H. Yamada, R.C. Barrett, and C.F. Quate, "Atomic force microscopy using a piezoresistive cantilever", Proceedings of Transducers 91, International Conference on Solid-State Sensors and Actuators (IEEE, Piscataway, NJ, 1991), 448-451.

[4] J. Thaysen, R. Marie, and A. Boisen "Cantilever-based biochemical sensor integrated in a microliquid handling system", Proceedings of the IEEE Workshop on Micro Electro Mechanical Systems, Interlaken, Switzerland (IEEE, Piscataway, NJ, 2001), 401-404.

[5] J.A. Harley and T.W. Kenny, "High-sensitivity piezoresistive cantilevers under 1000 Å thick", Appl. Phys. Lett. 75, 289, 1999.

[6] J.A. Harley and T.W Kenny, "1/f noise considerations for the design and process optimization of piezoresistive cantilevers", J. of Microelectromech. Syst., vol. 9, pp. 226-229, 2000.

[7] E. Cocheteau, C. Bergaud, B. Belier, L. Bary, R. Plana, "Formation of ultra-shallow p^+/n junctions using BF_2 implantation for the fabrication of improved piezoresistive cantilevers", Proceedings of Transducers'2001/Eurosensors XV, Munich, June 2001, pp 1070-1073.

[8] H. Chao, P. Griffin and J. Plummer, "Influence of dislocation loops created by amorphizing implants on point defects and boron diffusion in silicon", Appl. Phys. Lett., 68, pp. 3570-3572, 1996.

[9] T. Ondarçuhu, L. Nicu, S. Cholet, C. Bergaud, S. Gerder, C. Joachim, "A metallic microcantilever probes array incorporated in an atomic force microscope", Rev. Sci. Inst. 71, pp. 2087-2093, 2000.

[10] J. Liu and S. Mehta, "Effect of Ge-preamorphization on Junction Characteristics for Low Energy B implants", Mat.Res.Soc.Symp. Vol. 610, pp. 461-466, 2000.

[11] Y.F.Chong, K.L. Pey, A.T.S Wee, A. See, L. Chan, Y.F. Lu, W.D. Song, L.H. Chua, "Annealing of ultra-shallow p+/n junction by 248 nm excimer laser and rapid thermal processing with different preamorphization depths", Appl. Phys. Lett. 76, pp. 3197-3199, 2000.